

Temporal efficiencies of soil bioengineering techniques to mitigate geo-hydrological risks

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ABSTRACT

Natural hazards such as landslides, soil erosion and floods are increasingly affecting many regions of the world in relation to ongoing climate change and the abandonment of rural areas. In the last decades, the need to mitigate such phenomena and preserve natural resources, including landscapes, has motivated a number of local and national authorities to promote the use of soil bioengineering techniques. Consequently, these techniques have been increasingly used with variable success rates. This study analysed the efficiencies of different bioengineering structures to mitigate geo-hydrological risks by examining the interventions installed between 2007 and 2013 in the *Avellino* Province southern Italy. To this end, a specific project consistency analysis and functionality classification were carried out and the causes of inefficiencies were identified. The analysis showed that after a few years, only a small number of the installed bioengineering structures were fully functional and efficient. Overall, the installed structures were generally affected by maintenance issues and in many cases they suffered from design and execution issues, inducing a generally lower degree of efficiency, with most of them classified as 'not very efficient'. The conclusions of this work are that i) the long-term efficiency of a bioengineering structure is related to its correct design, installation, and maintenance; ii) the design of a bioengineering structure should account for the geological, geotechnical and hydrological characteristics of the area of interest, and iii) maintenance must not affect the short-term efficiency of a structure, but may affect the long-term efficiency.

1. Introduction

Natural phenomena such as landslides, soil erosion, and floods have severe consequences worldwide (Fernandes and Guimar, 2016; Lin et al., 2006; Perez et al., 2017; Poesen, 2017; Poesen et al., 2003). In many regions of the world, the increased frequency of such events is consistently related to ongoing climate change (Gariano and Guzzetti, 2016; Messeri et al., 2015; Revellino et al., 2019) and is considered to be driven by an irreversible abandonment of good practices in land management, which is also connected to the depopulation of rural areas (Brandolini et al., 2018; Di Martire et al., 2012; Lasanta et al., 2000; Tarolli et al., 2014). Geo-hydrological risk mitigation is an important topic for land-use planners, technicians, and researchers (Arabameri et al., 2021; Canuti et al., 2000; Carotenuto et al., 2017; Di Napoli et al., 2020a, 2021; van Westen et al., 1997; Novellino et al., 2021). From this perspective, soil conservation is a primary objective in the context of protection measurement design, which is also suitable for the protection

of inhabited areas and natural attractors, preventing natural disasters (Cavaillé et al., 2015). In Italy, many regions, such as *Emilia Romagna*, *Lazio*, and *Campania* etc., have legislated the matter.

In *Campania*, a regulation for the application of soil bioengineering techniques to geo-hydrological risk mitigation has been adopted since 2002, providing regulatory definitions related to these applications and descriptive datasheets for specific technical solutions. Between 2002 and 2013, in association with this document and through the '*Programma Operativo Regionale*' (POR, translated as 'Regional Operative Program'), the regional government of *Campania* financed bioengineering-based measurements for forestry restoration and geo-hydrological risks mitigation. In most cases, regional funding was used to restore streams, whereas only in a few cases were the works carried out for the recovery of the areas affected by landslides (Calcaterra et al., 2006, 2004).

Bioengineering techniques are suitable for improving surface drainage and protecting slopes against shallow landslides and surface

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erosion. These low-impact techniques involve the use of plants (or parts of plants) for engineering applications to control soil erosion, shallow mass movements, and streambank stability (Bischetti et al., 2014; Yildiz et al., 2019; Zhang et al., 2014). As a multidisciplinary subject, the design of bioengineering structures requires contributions from specialists involved in different fields, such as geologists, geotechnical engineers, botanists, landscape architects, and hydrologists (Freer, 1991). Generally, bioengineering structures consist of associations between non-living natural elements and plants. The presence of plants and their development increasingly ensures the stability of slopes and streambanks through both mechanical and hydrological effects (e.g. additional cohesion from roots) (Bischetti et al., 2009; Schmidt et al., 2011). For instance, the presence of vegetation enhances the resisting force in the form of additional cohesion from the roots and reduces the pore-water pressure, thus reducing the forces acting on the weight of the soil mass by absorbing moisture, reducing surface runoff, intercepting rainfall and promoting evapotranspiration (Freer, 1991; Marques et al., 2007; Molina et al., 2007; Price et al., 1998; Ruiz-Colmenero et al., 2013; Yang et al., 2019; Zhang et al., 2001). In this context, rapid removal of vegetation (i.e. due to wildfires and deforestation) might promote slope failures (Di Napoli et al., 2020b; Rengers et al., 2020). Moreover, the presence of vegetation can negatively influence slope stability, depending on its position along a slope. Indeed, while the presence of biomass at the slope toe increases its overall stability, its presence upslope can increase the driving forces that promote slope failure (Greenwood et al., 2004; Schwarz et al., 2010). The use of bioengineering techniques in erosion control and slope stabilisation has some differences compared with traditional methods because of the limited control of the properties of the stabilising material. In addition, the action of vegetation is somewhat limited to a specific root penetration depth, making such techniques ineffective against deep-seated landslides and large embankments. The control of these types of hazards using herbaceous and woody vegetation through bioengineering approaches remains a major challenge (Dhital and Tang, 2015; Pepe et al., 2020; Rey et al., 2019). Bioengineering structure design requires comprehension of the interdependency of hydrological, ecological, and biophysical processes, and the extent to which these processes influence the efficiency and durability of structures. Indeed, the use of living plants as structural features leads to a different response in terms of common structural measurements (Graf and Frei, 2013; Tardío and Mickovski, 2016), and the long-term behaviour needs to be understood in terms of limits and perspective efficiency. Moreover, such measurements, representing a compromise between process mitigation through

traditional engineering techniques and instability, have specific functions and adaptability to slope conditions. Their intrinsic complexity makes such interventions susceptible to a variety of issues that must be carefully considered to prevent efficiency loss. There are many potential issues related to the complexity of a bioengineering structure with respect to potential slope process mitigation (Fig. 1).

On this basis, although several aspects related to the design and application of bioengineering structures in land degradation process mitigation have been previously analysed, information on the efficiencies of such structures as well as their correct design and regular maintenance is still lacking (Romano et al., 2016). In this context, the present work contributes to the methods used for evaluating the efficiencies of temporal bioengineering structures, and highlights the advantage and disadvantage of such measurements to mitigate geohydrological risks. To this end, bioengineering structures designed and installed in specific sectors of *Avellino* Province in southern Italy between 2007 and 2013 were analysed and their efficiencies were monitored ~3 years after their installation. To supplement the analysis, the consistency of the project was analysed and related to the estimated efficiencies.

2. Study area

Avellino Province covers an area of 2805 km² in the Apennine mountains regions of southern Italy. It is characterised by a complex geologic and geomorphologic setting that significantly influences the exposure of the territory to degradation processes such as deep-seated and shallow landslides, floods, and erosion (Guerriero et al., 2019a; Pinto et al., 2016; Fig. 1). Landslides and floods are mostly triggered by intense rainfall events and are frequently associated with the erosion process (Revellino et al., 2019). As pointed out by the Italian National Institute for Environmental Protection and Research (ISPRA, 2018), while high and very high landslide hazard areas cover approximately 655 km² (i.e. 23% of the province), areas characterised by a high flood hazard extend over approximately 22 km² (i.e. 1% of the territory). Overall, of the 118 municipalities within the province, 75 are characterised by high to very high landslide hazards and high flood hazards.

The geological and geomorphological complexity of *Avellino* Province exposes it to spatially differentiated landslides, floods, and erosional processes (Guerriero et al., 2019b; Santo et al., 2018, 2017). The western sector of the province, where limestone crops out (Apennine range, Fig. 2, sector e), is characterised by higher average acclivity (~35°) and a widespread pyroclastic cover (thickness of 0.5–5 m) that is

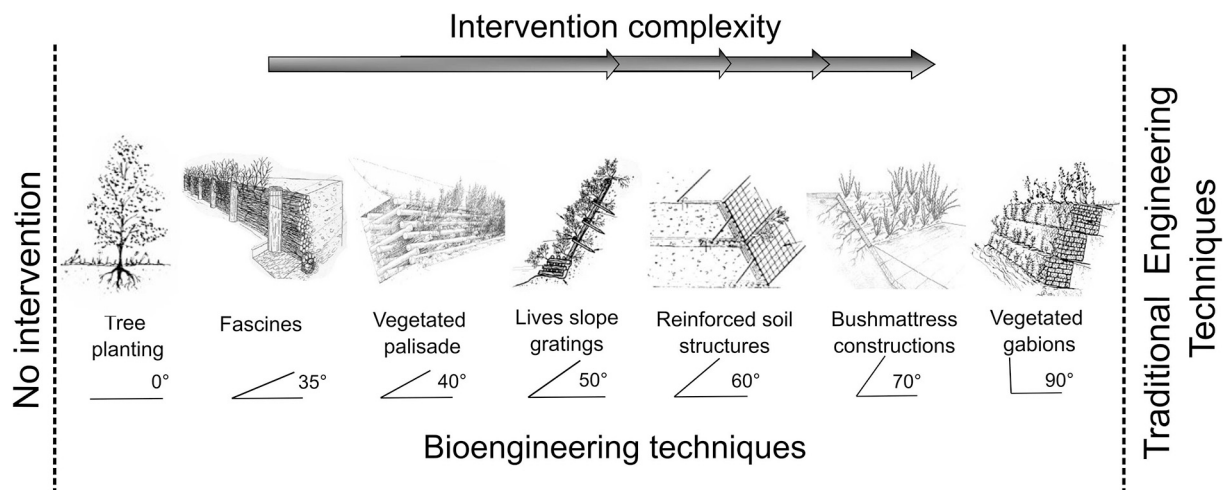


Fig. 1. Schematic representation of the complexity and associated potential issues of bioengineering interventions, reproduced with kind permission from Cornellini and Sauli (2012). These techniques can be employed only in specific applications namely shallow landslide and low magnitude phenomena. Starting from the field of no intervention the complexity increases up to traditional engineering techniques where the use of vegetation is insufficient.

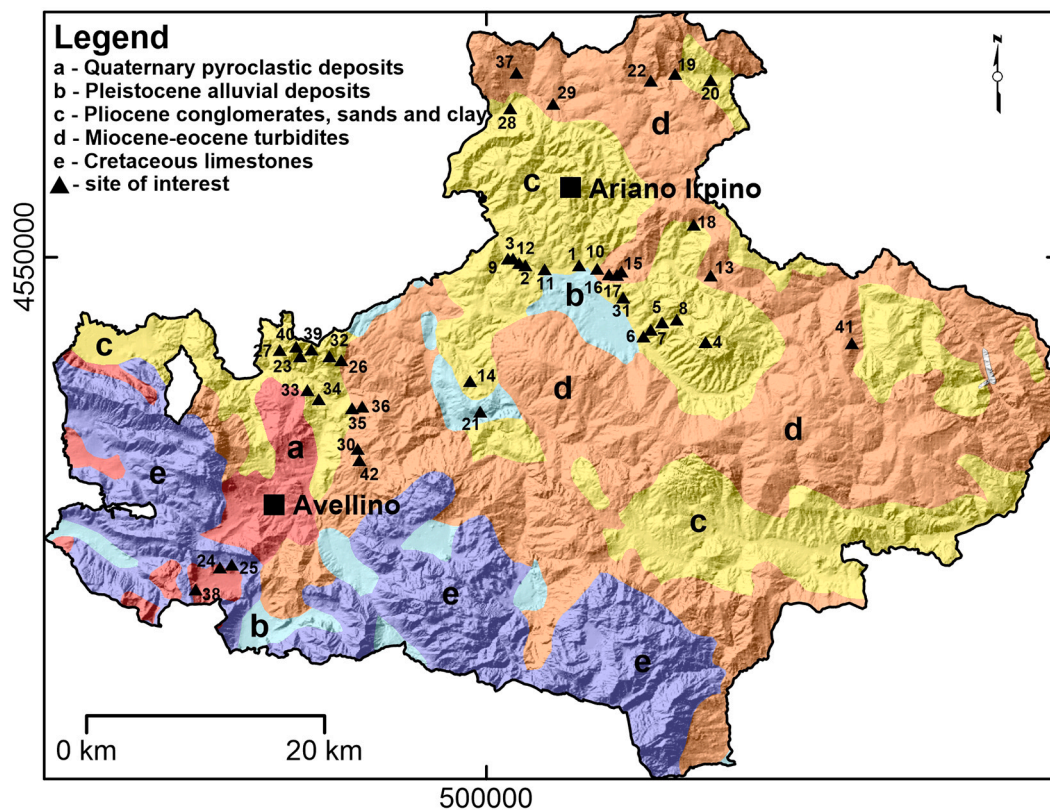


Fig. 2. Geological map of Avellino Province. The letters represent deposits cropping out within the study area. Black triangles indicate the positions of the sites of interest considered in this study.

susceptible to fast flow-like landslides triggered by intense rainfall events (Calcaterra et al., 2003; Fiorillo et al., 2001). Translational landslides occur only locally, involving both pyroclastic cover and underlining deposits (Guerriero et al., 2019a). In this sector, major flood events are related to intense and severe rainfall and are commonly associated with diffuse erosion. Moving eastward, the central sector of the province is characterised by the presence of sub-Apennine hills comprised of local flyschoid deposits covered by pyroclastic soils (Fig. 2, sector d). In this zone, slope failure is commonly larger and slower than that in the western sector, and also has a dominant translational component (Guerriero et al., 2014). Widespread agricultural land use makes this zone particularly susceptible to extensive erosion related to intense rainfall events. Flood events are concentrated along high-order segments of the hydrographic network and mainly occur because of brief and intense rainfall in summer and prolonged rainfall in autumn. The eastern sector of the province, towards Puglia, is dominated by large slow-moving and flow-type landslides associated with deep-seated gravitational features (Di Martire et al., 2016; Guerriero et al., 2014; Pinto et al., 2016). This type of landslide is related to the prevailing clayey nature of outcropping rocks (Fig. 2, sector d). These landslides are mainly intermittent, with periodic reactivations in conjunction with major meteoric and/or seismic events. Floods in the form of flash and debris floods are less frequent than those in the western sector of the province and occur in association with storms. Erosion processes are particularly effective and affect both slopes and riverbanks because of the intense agricultural use of the territory.

3. Method

From the perspective of shallow landslides and flood/erosion mitigation, and as the first step in the efficiency analysis, an inventory was prepared of the bioengineering structural interventions installed during 2007–2013 along slopes and river segments of Avellino Province. The

inventory was prepared through an archive analysis of projects submitted to the Campania's program for financial support ('Programma di Sviluppo Rurale', translated as Rural Development Program). Subsequently, each project was analysed in terms of overall composition and consistency with the technical recommendations provided by national and regional regulations. In particular, the quality of each project was assessed by considering the presence or absence of recommended technical reports, such as hydraulic reports, geological and geotechnical reports and, agronomist contributions. For this purpose, as recommended by the specific regional regulations, seven types of technical report were analysed as follows: i) geological reports, ii) geotechnical reports, iii) stability analysis reports, iv) hydrologic analysis reports, v) agronomist reports, vi) biotechnical analysis reports, and vii) prescriptions for vegetation maintenance. Project quality analysis was completed by assigning a final score to each project as a function of the presence/absence of each type of technical report (i.e. 1 to 7). This approach was chosen because of its easy applicability in different contexts without any specific information about report quality; however, it is clear that in specific environmental conditions and in the presence of different forcing (e.g. soil erosion and landslide), the weight of each report might deviate from the unit. On this basis, our chosen approach must be considered as a requisite for improving method transferability.

After the project quality analysis, specific in-situ inspections were performed. Such activities aimed to verify the bioengineering structure state 3 years (on average) after their construction. This time-span was chosen considering the average time needed for the engraftment and initial development of vegetation species commonly used in bioengineering structures. Based on field observations completed during the inspections, an evaluation criterion was established to provide an estimation of the conditions of the bioengineering structures included in the inventory. Specifically, field surveys carried out between January and April 2018 identified the widespread presence of issues related to the integrity of bioengineering structures, their functionality, and the

degree of integration with the surrounding environment. On this premise, as indicated in Table 1, four classes were considered to rate the functionality of the structures. In particular, the first class identifies those structures affected by diffuse damage, and even those that are not-existent. The fourth class identifies working structures that, after a period of adaptation, are fully integrated with the landscape.

Potential causes of inefficiency were analysed and registered to supplement the analysis during the field surveys. Accordingly, three main factors of weakness/deterioration were detected: 1) problems related to the design of a bioengineering structure (D, Fig. 3a), 2) execution errors during structure installation (E, Fig. 3b), and 3) lack of maintenance (M, Fig. 3c). Structural design issues related to deviations from the standards reported in the technical reports provided by the authority of the Campania Region, and to a lack of supporting structures (e.g. dissipation basin below a wooden check dam) or under-sizing of bioengineering structures. Execution issues correspond to the use of inappropriate materials and/or undersized elements unforeseen in the project. Maintenance issues related to the lack of living plants or bioengineering structure elements, as well as the loss of efficiency due to wood decay has been considered.

The worst condition was realised by the coexistence of problems related to both design and installation execution (D/E). The latter represents the boundary conditions of the analysis. On this basis, and considering the field-estimated functionality, an efficiency analysis was completed using a matrix-based approach to examine the relationship between the bioengineering structure functionality and potential causes of a reduced working capability. Thus, this study aims to support the interpretation of the expected mid-term efficiency of interventions and provide a discussion on the suitability of each type of structure in mitigating specific processes in the well-known context of Avellino Province.

The matrix-based approach allowed to determine a specific efficiency class for each type of bioengineering structures in terms of potential design and management issues. Four classes were established: I) 'Not Efficient' (NE), including not-working structures with problems connected to mistakes in design and installation; II) 'Not Very Efficient' (NVE) and III) 'Quite Efficient' (QE), including structures with problems connected to mistakes in design (i.e. related to the lack of technical reports) and installation, subject to maintenance after realisation; and IV) 'Efficient' (E), including structures that are correctly designed, installed, and maintained (i.e. in full compliance with the regulations), and fully working and integrated within the environment after 3 years (Fig. 4). To supplement our interpretation of the efficiency of a given bioengineering structure, further comparison between structural efficiency and land use was made, based on data available in the official pan-European inventory of CORINE (2018).

4. Results

The results of the archive analysis showed that, across the territory of Avellino Province, a total of 43 bioengineering-based land degradation

mitigation projects were financed during 2007–2013 (see the Supplementary materials). Bioengineering structures are currently mostly located in the eastern and northern sectors of the province (Fig. 2).

These structures mainly consist of vegetated gabions and palisades, wooden check dams, tree planting, and bush mattresses. As a function of the scope, reinforced and vegetated slopes, geotextiles, osieries, live slope gratings, and riverbed protections have been used (Fig. 5). Project analyses and field surveys revealed that different techniques have been used simultaneously with the extensive use of plants. The quality analysis indicated that many projects have gaps in their technical documents (Fig. 6a). No project contained all of the seven recommended reports: 28% had six of the seven reports, 60% had three to five of the seven reports and 12% had two to three reports.

Many projects included reports describing the geological characteristics of an installation area and protocols in vegetation, while reports describing the geotechnical analysis of materials and slope stability tests were found to be frequently missing (Fig. 6b). In many cases, reports describing the biotechnical properties of plants and trees were missing and, in half of the cases, a hydraulic report was not present.

Field inspections revealed that, a few years after the installation, only 7% of the interventions were fully working and appeared to be integrated into the local landscape (i.e. functionality class IV; Fig. 6c). Of the remaining interventions (i.e. 93%), 25% were working but appeared to be suffering the early stages of decay in specific components and lacked of maintenance (i.e. functionality class III; e.g. woody elements), 58% had relevant functionality problems due to design issues and the use of unsuitable materials during installation (i.e. functionality class II; e.g. undersized woody elements), and the remaining 10% were either no longer present or not working due to diffuse damage (i.e. functionality class I; Fig. 6c). Except for structures classified as fully working, for which only maintenance issues were observed, functionality problems were related to either design, execution, or maintenance issues, as well as a potential combination of design and execution issues. No relevant differences in issue occurrence were identified (Fig. 6d). In addition, the result of field investigation indicated that the studied bioengineering structures exhibited a differentiated level of functionality (Fig. 7). This include: i) structures that were no longer present (i.e. class I; Fig. 7a), ii) structures with reduced functionality due to evident design and maintenance issues (i.e. class II; Fig. 7b), iii) structures with only minor issues (i.e. class III; Fig. 7c), and iv) structures consistently working and partially integrated within the environment with only maintenance issues (class IV, Fig. 7d). Moreover, the analysis of the potential relationships between the locations of the studied bioengineering structures, their estimated efficiencies and local land use indicated that most structures were installed within agricultural areas and forests; however, no particular relationship existed between the efficiencies of structure and land use (Fig. 8). The efficiency analysis of inventoried bioengineering structure showed that, approximately 8% of the structures were fully efficient and integrated into the landscape (E). Of the remaining 92%, approximately 20% were quite efficient (QE), 50% were not very efficient (NV) and the remaining 22% were not efficient (NE).

5. Discussion

The analysis of the efficiencies of the studied bioengineering structures showed that most of the structures endowed by the Campania Region between 2007 and 2013 and installed in Avellino Province were either not very efficient or not working 3 years (on average) after their installation. Only a small number were identified as being fully efficient and substantially integrated into the landscape. Project inconsistencies with the technical recommendations of the regional authority were identified, whereby least one recommended technical report was not present in all cases. According to the available data, it was not possible to identify a consistent functional relationship between the final efficiency and project quality score (see 'Quality of projects' and 'Efficiency class' columns of the table in the Supplementary materials). This effect

Table 1

Description of functionality classes description based on field observations completed a few years after the installation of structures.

Functionality	Description
I	Very damaged to non-existent structures: many parts of a structure have been removed or are very deteriorated
II	Obvious functionality problems: a structure is still intact but its functionality is limited by design issues and poor building materials
III	Functional with deteriorated parts: an intervention has good functionality but problems of early-stage degradation have been detected
IV	Functional and in harmony with the landscape: a structure is completely in harmony with the landscape and its full functionality is ensured by constant maintenance



Fig. 3. Examples of a) design, b) execution, and c) maintenance issues and eventual related effects on bioengineering structures.

Efficiency Matrix		Functionality Classes			
		I	II	III	IV
		0 - 25	26 - 50	51 - 75	76 - 100
C a u s e s	Design/Execution	Not Efficient		Quite Efficient	
	Design	Not Very Efficient		Quite Efficient	
	Execution	Not Very Efficient		Quite Efficient	
	Maintenance	Not Very Efficient		Efficient	

Fig. 4. Matrix used for the efficiency analysis of bioengineering structures installed in *Avellino* Province. The numbers in the functionality classes refer to the description in [Table 1](#).

might be related to the absence of projects fully consistent with the recommendations of technical guidelines (i.e. the presence of all the recommended reports) and to the frequent presence of issues related both to installation drawbacks and a lack of maintenance. Additional issues corresponding to the use of inconsistent materials during installation contributed to the overall low efficiency. The design of bioengineering structures requires knowledge of the given site conditions and material features and properties ([Romano et al., 2016](#)). In addition, the

lacking of geotechnical reports and stability analyses, is a major cause of the poor efficiency of a structure installed to mitigate slope instability, such as the association of vegetated gabions, brush matter and live grated slopes. These documents are essential for the correct design of a structure to mitigate landslide events and associated erosional phenomena. The hydrologic analysis report is also relevant, especially in the context of erosion and flood mitigation. Indeed, in several cases, many of the functionality aspects of structures involving vegetated gabions were related to erosion at the basal level, presumably due to the absence of an evaluation of potential the peak discharge expected for the specific creek or river (e.g. [Fig. 7b](#)). The investigations carried out at the end of the *POR* of 2000–2006 had already highlighted critical issues related to the use of bioengineering techniques, mainly due to the lack of specific technical reports ([Calcaterra et al., 2006](#)). In addition to design issues, drawbacks related to building material inconsistencies were frequently observed. For instance, the use of undersized woody elements in slope gratings and palisades predicated their functionality in many cases ([Fig. 7a, c](#)). As a consequence, these structures were either not efficient or not very efficient.

The few structures identified as fully efficient suffered only from a maintenance issue that, if solved in the short term, could ensure their mid to long-term functionality. Bioengineering structures, involving the use of different plant species, acquire a growing functionality over time according to the biological cycle ([Florineth and Molon, 2004](#)). This makes such mitigation measurements particularly susceptible to accelerated efficiency loss in the case of vegetation maintenance. In this

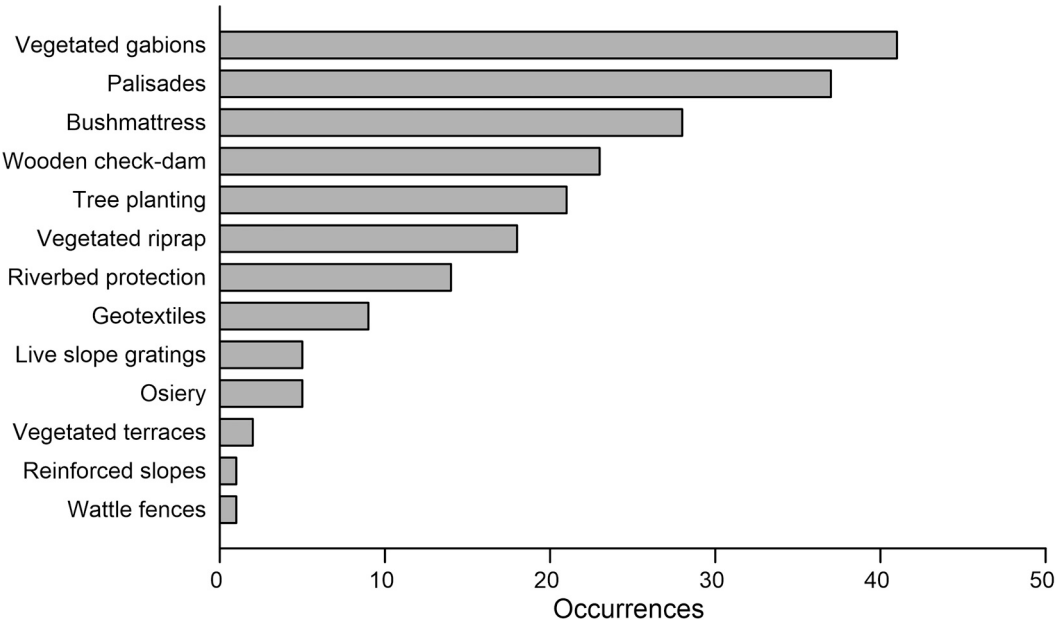


Fig. 5. Occurrences of specific structures in the considered bioengineering interventions.

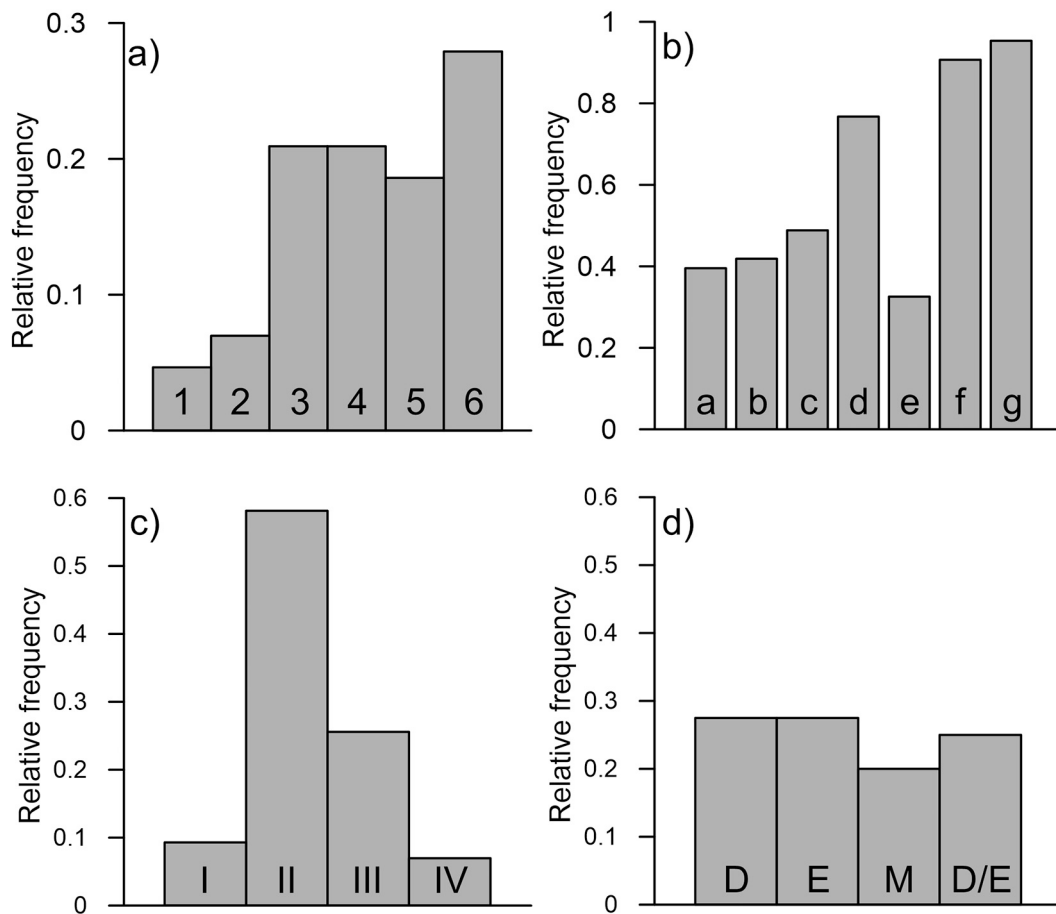


Fig. 6. Graphs showing a) project consistency with respect to a number of recommended reports (i.e. 1 to 7), b) relative presence of recommended reports (a. geotechnical, b. stability analysis, c. rainfall analysis, d. agronomical, e. biotechnical, f. vegetation management, and g. geological), c) functionality distribution of bioengineering structures (efficiency levels of I to IV) and d) observed issue distribution (D: design; E: execution; M: maintenance; D/E: design and execution).

context, the biotechnical properties of plants, planting methods, and their maintenance that should not be overlooked because they ensure the ‘growing’ mitigating action of structures in the mid- to long-term following the development of root systems. Vegetative planting represents one of the most important corrective measures in the case of landslides and/or erosive issues. According to the well-developed literature on experimental studies (Gerstgraser, 1998; Tobias, 1994), the peak and residual resistance value of a given soil increase at least two-fold because of the presence of roots in samples containing living root systems. However, in the analysed projects in the study, most of the maintenance problems were related to a lack of vegetation. If the vegetation associated with gabions or slope gratings does not develop in 1 to 3 years, maintenance in terms of new planting is required to avoid the permanent loss of functionality that might determine the loss of the mitigating effect of the structure. The importance of maintenance highlighted by the analysis is related to substituting the action of non-living materials with the action of living material (i.e., trees and plants). A further problem concerns the ability of the local management department and employees’ qualifications. The need for specific competencies related to the engineering, agronomic, and botanic aspects of bioengineering structures represent a major limitation restricting the use of such measurements compared with the European Alpine environment (Florineth and Molon, 2004).

Traditional building materials such as wood, stones, and plants, can be used in combination with new synthetic but biodegradable materials to reduce the maintenance time and increase the stabilising action of non-living materials. The use of more technologically advanced materials such as iron mesh, geotextiles, geogrids, or plastic geocells has also

led to the development of new techniques (Dutta and Mandal, 2016; Prambauer et al., 2019; Vianna et al., 2020). A valid example of new technology is the use of reinforced soil structures used only once in the examined interventions. Such materials are now generally included in combined work associated with planting, cutting, or seeding.

Among the analysed interventions, bioengineering structures such as vegetated gabions were present at all but two of the studied sites. Gabions associated with grated slopes and bush mattresses are mainly used to mitigate and prevent slope instability, while gabions associated with reinforced slopes, vegetated riprap, and palisades are mostly used to reinforce riverbanks to mitigate creek and river erosion (Recking et al., 2019; Tisserant et al., 2020). As found in Calcaterra et al. (2006) and the present study, in many of the inventoried cases, adopted interventions are mainly aimed at mitigating erosive phenomena along rivers, while only a small number of projects were aimed at mitigating shallow landslides. Despite this evidence, shallow landslides constitute a meaningful proportion of all landslides detected in the study area and appear to be pervasive in the outcrop areas of both Pliocene and Miocene pelitic formation deposits (Fig. 2c, d; Calcaterra et al., 2003). They typically start as a consequence of moderate rainfall and concentrate where the soil cover has a cohesive nature. Many such landslides occur as a result of vegetation cover loss. In some cases, shallow landslides, extending to only a few meters below the ground surface, originate in association with severe surface erosion from run-off phenomena (Cevasco et al., 2014; Montgomery et al., 2002). If erosion is allowed to proceed unconfined, its effects might extend to a much larger damaged slope section. Under these conditions, the use of bioengineering structures such as fascines and slope gratings, might prevent such evolution

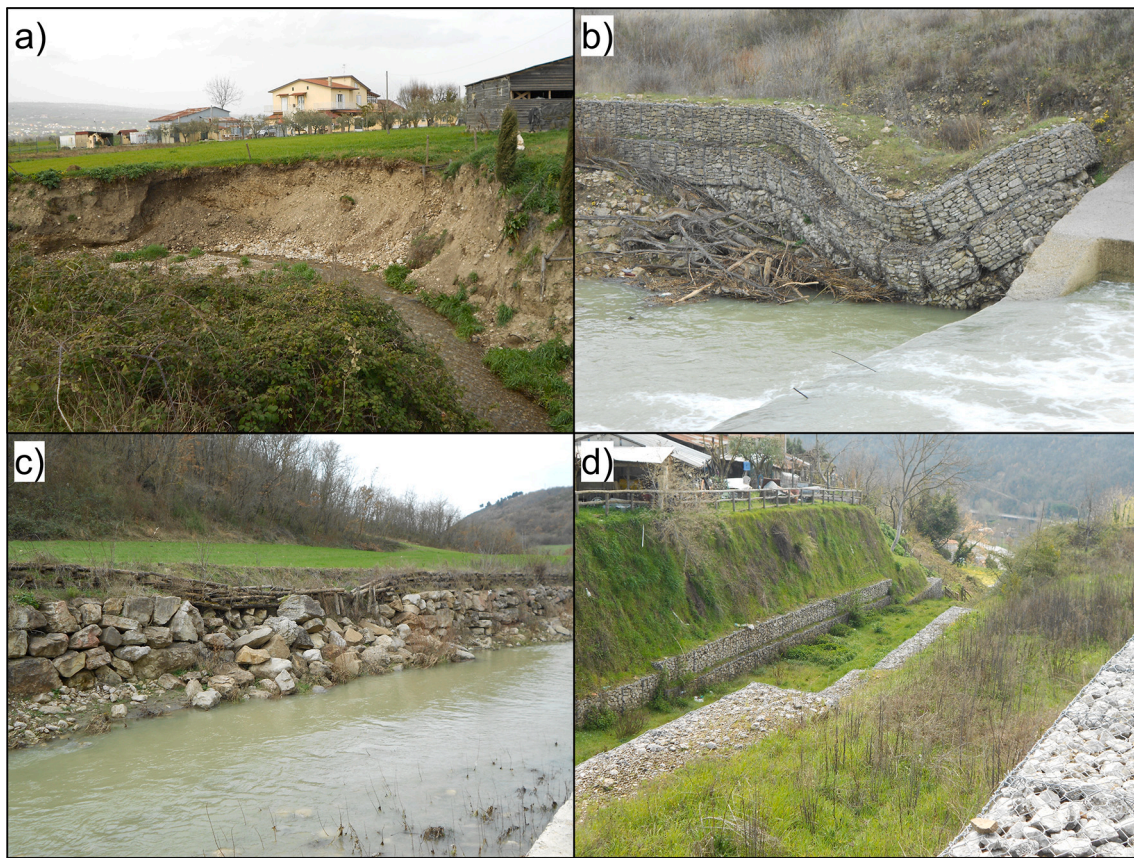


Fig. 7. Examples of associations of bioengineering structures with different levels of functionality. a) non existent bioengineering structures (functionality class I); b) intact vegetated gabions with evident functionality limits due to design issues, (functionality class II); c) working bioengineering structures with local issues (functionality class II); d) fully working (functionality class IV), vegetated gabions associated with reinforced soil.

and contribute to slope stabilisation (Richet et al., 2017). Under specific conditions, shallow landslides can be triggered by creek and river erosion affecting creek-valley flanks and riverbanks. Bioengineering structures are suitable for preventing such events, mitigating the erosional effects of running water, and stabilising banks. The best method to control landslides on riverbanks is to create a vegetated riprap along slope toe. Heavy blocks positioned at the slope toe can increase the resistance to failure. The minimum block size can be estimated from the largest boulders in the riverbed. When suitably sized rocks are not available on-site, vegetative techniques can be used (e.g., tree planting and wooden elements). Some examples are reported in Singh (2010), whereby many landslides and debris flows in different watersheds were controlled by these methods. Moreover, the combined use of gabions and vegetated palisades has proved to be very efficient for this purpose.

In recent decades, the Italian government has allocated substantial resources to mitigate landslides, floods, and related erosional processes. Between 1990 and 2010, annual funds fluctuated between approximately 200 and 400 million Euros. Unfortunately, financial resources from 2011 to 2016 were inadequate despite flood events that caused serious damage, such as those occurring in Cinque Terre, in Genoa, Val di Vara, in Sardinia, and Benevento in Campania (Brandolini et al., 2012; Cevasco et al., 2015, 2013; Guerriero et al., 2019a; Revellino et al., 2019; Righini et al., 2017). In 2019, a national plan was approved to provide resources equal to approximately 10.9 billion Euros. In this context, the contribution of bioengineering structures to geo-hydrological risk mitigation is still relatively small. Considering the orientation of European guidelines on sustainable development for member states, such a tendency should be modified to support these types of measurements from the perspective of landslide, flood, and

erosion mitigation, especially in protected areas. It is clear that, as highlighted by the analysis in this study, such measurements require specific knowledge of the system and a specifically developed maintenance plan to ensure long-term durability of measurements through the concept of mitigating action substitution between non-living and living elements. Accordingly, the proposed method might be a useful tool for evaluating the ongoing and near-future efficiencies of bioengineering structures in a range of environmental contexts. The reduced complexity of the method, which is simple enough to account for commonly available data, allows for exportability in contexts differing from those analysed in the present study. In fact, shallow landslides and soil erosion are ubiquitous phenomena that can be mitigated by bioengineering techniques.

6. Conclusions

Between 2007 and 2013, 43 bioengineering projects were financed by the authority of the Campania region in southern Italy. An analysis of the efficiencies of interventions installed in specific sectors of Avellino Province in terms of project consistency and design, execution, and maintenance issues, was carried out. A specific functionality classification was adopted. The analysis results indicated that several issues compromised the mid-to-long-term efficiencies of bioengineering measurements adopted to mitigate geo-hydrological risks due to landslides, floods, and related erosion. The project analysis revealed substantial gaps in the measurement design. Field inspections carried out ~3 years after installation showed that, in many cases, bioengineering measurements experienced a substantial loss in functionality due to design, execution, and maintenance issues. The worst functionality was encountered when both the design and execution issues were present.

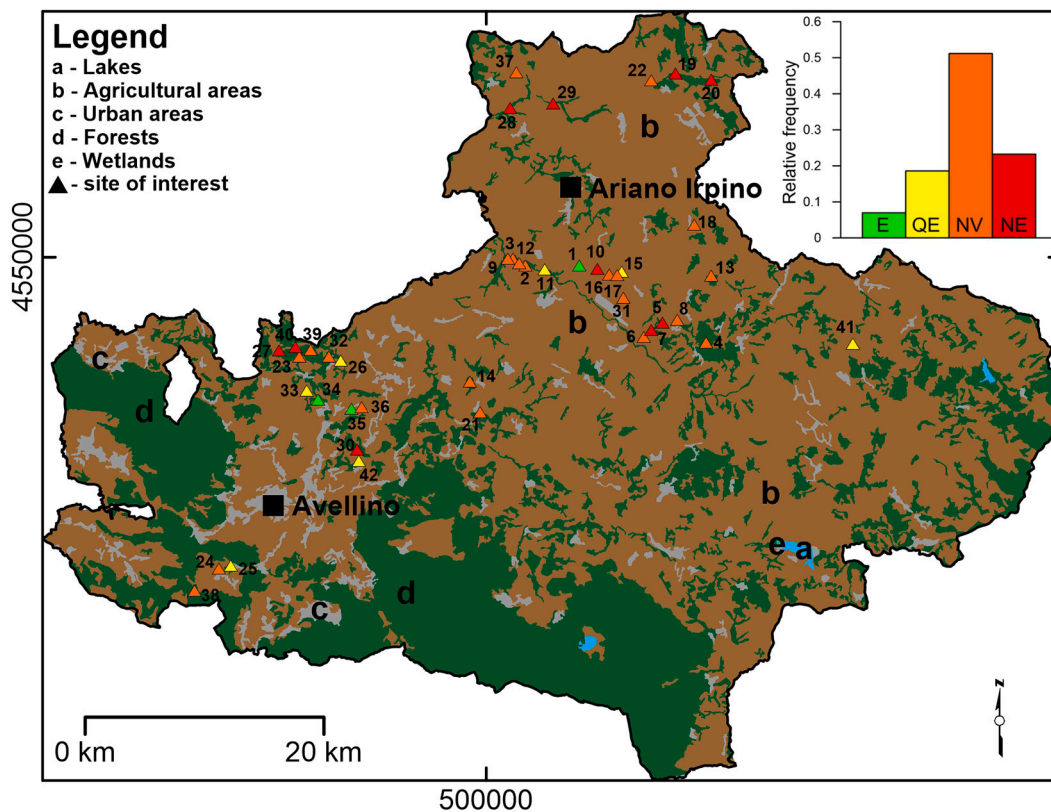


Fig. 8. Map showing the distribution and efficiencies of bioengineering structures, as derived by the application of the proposed matrix-based approach for Avellino Province. The base-map shows land use, and the inset graph shows the distribution of identified efficiency classes.

Field observations also highlighted that the studied bioengineering measurements required a specific maintenance plan to improve and maintain a consistent efficiency over the long term. This aspect plays a crucial role in the development of biotechnological characteristics over time. A fully functional and efficient association of structures was found in the case of better designed and well-installed measurements with the only issue being the need for periodic maintenance. The overall conclusions of this study are as follow: *i*) the long-term efficiency of a bioengineering measurement is related to its correct design, installation, and maintenance; *ii*) the design of a bioengineering structure should mandatorily account for the geological, geotechnical, and hydrological characteristics of the area of interest, and *iii*) maintenance must not affect the short-term efficiency of a structure, but may affect the long-term efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2021.106338>.

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